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# Abrupt Climate Change Experiments: The Role of Freshwater, Ice Sheets and Deglacial Warming for the Atlantic Meridional Overturning Circulation

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**Abstract:** In this review paper we summarise a series of numerical abrupt climate change experiments in the context deglaciation. The effects of global warming, deglacial freshwater, and ice sheets for the termination of the last ice age are examined in a model of intermediate complexity and a fully coupled, coarse-resolution climate model. We find that gradual deglacial global warming induces an abrupt strengthening of the Atlantic Meridional Overturning Circulation (AMOC). More generally, if the system is in a bistable window, a linear forcing can yield non-linear AMOC changes. In this sense Northern Hemisphere freshwater hosing only modulates the timing of the AMOC onset. Furthermore, Northern Hemisphere freshwater hosing weakens the AMOC with a potential overshoot, after the freshwater forcing has stopped. Therefore, as a further hypothesis the onset of Bølling/Allerød (B/A) interstadial with warming over Greenland could be related to an increase in AMOC, which is induced by a declining freshwater forcing prior to or in parallel with the transition. In contrast, hosing in the Southern Hemisphere has a relatively minor influence on the AMOC. The associated climate signatures and mechanisms are explored and discussed in this study.

**Zusammenfassung:** In diesem Übersichtsbeitrag stellen wir eine Reihe von numerischen Experimenten zum abrupten Klimawandel am Ende der letzten Eiszeit vor. Die Auswirkungen der globalen Erwärmung, des deglazialen Süßwassers und der Eisschilde auf die Termination und Ozeanzirkulation werden in einem Modell mittlerer Komplexität und einem vollständig gekoppelten Klimamodell untersucht. Unsere Modellergebnisse vermitteln Einsichten in die abrupte Erwärmung in der Nordhemisphäre, das sogenannte Bølling/Allerød (B/A) Nordatlantik Interstadial, und der deglazialen Schmelzwasserpulse. Wir stellen fest, dass die deglaziale globale Erwärmung eine Verstärkung der atlantische Umwälzbewegung (Atlantic Meridional Overturning Circulation, AMOC) induziert. Wenn sich das System in einem bistabilen Fenster bewegt, kann ein linearer Antrieb zu einer nichtlinearen Antwort in der AMOC führen, wobei das Schmelzwasser den Zeitpunkt für das B/A verändern kann und die AMOC schwächt. Bei der Rückkehr in den Usprungszustand kann die AMOC überschwingen, d.h. sie zeigt stärkere Amplituden als unter ungestörten Bedingungen. Deglaziales Süßwasser in der südlichen Hemisphäre hat einen relativ kleinen Effekt auf die AMOC. Als weitere, alternative Hypothese zum Vorhandensein des B/A-Interstadials könnte auch die Abwesenheit von Süßwasser beigetragen haben. Dadurch wird die AMOC verstärkt und infolgedessen Grönland erwärmt. Signaturen und Mechanismen dieser Prozesse werden in diesem Beitrag untersucht und diskutiert.

## INTRODUCTION

Within glacial periods, and especially well documented during the last one, there are dramatic climate transitions, including high latitude temperature changes approaching the same magnitude as the glacial cycle itself. Signals with world-wide teleconnections are recorded in archives from the polar ice caps, high to middle latitude marine sediments, lake sediments and continental loess sections (e.g., BENDER et al. 1999). FLOHN (1986) proposed as a concept of abrupt climate change to include both, singular events and catastrophes such as extreme El Niños, as well as discontinuities in paleoclimate indices. One hypothesis for explaining deglacial as well as Dansgaard-Oeschger climatic transitions is that the Atlantic meridional overturning circulation (AMOC) flips between different modes, with warm intervals reflecting periods of strong deep water formation in the northern North Atlantic and *vice versa* (GANOPOLSKI & RAHMSTORF 2001). As an alternative approach, the underlying dynamics with its bifurcation can directly be estimated from data (KWASNIOK & LOHMANN 2009, LIVINA et al. 2011, KWASNIOK & LOHMANN 2012). In this study we discuss several hypotheses of ocean dynamics during glacial terminations, including the effect of global warming, freshwater history, ice-sheet height, and orbital forcing.

The overarching goal of this article is to explore different hypotheses regarding abrupt millennial-scale deglacial climate variabilty and the glacial termination. In particular, the investigations aim at a better understanding of the Bølling/Allerød (B/A) (14,700–12,700 years before present) North Atlantic interstadial dynamics and their relation to deglacial meltwater pulses. To study the glacial dynamics, we use models with different level of complexity, an ocean general circulation model (OGCM) coupled to an energy balance of the atmosphere, as well as the Earth system model COSMOS, consisting of an atmosphere-ocean general circulation model (AOGCM), including a dynamical vegetation module.

There are numerous approaches to understand the last termination. The question is what causes the abrupt warming at the onset of the Bølling as seen in the Greenland ice cores. There is a clear antiphasing seen in the deglaciation interval between 20 and 10 ka. During the first half of this period, Antarctica steadily warmed, but little change occurred in Greenland. Then, at the time when Greenland's climate underwent an abrupt warming, the warming in Antarctica stopped. A possible hypothesis can be that a sudden increase of the northward heat transport draws more heat from the south, and leads to a strong warming in the north. This "heat piracy" from the South Atlantic has been formulated by CROWLEY (1992). A logical consequence of this heat piracy is the Antarctic Cold Reversal (ACR) during the Northern Hemisphere warm Bølling/Allerød.

Additional freshwater forcing complicates the situation. ROCHE et al. (2010) explored the impact of freshwater

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pulses with respect to different geographical locations. Lohmann & Schulz (2000) performed freshwater sensitivity studies for different ocean states with and without North Atlantic overflow water. Liu et al. (2009) showed in their experiments, covering the deglaciation that a Bølling-type overshoot can be obtained when the freshwater hosing history has been prescribed in such a way that the reconstructed temperatures and AMOC are resembled. Other important parameters are the ice sheets and greenhouse gases. During times when the ice sheets were at intermediate ice-sheet volume, large millenial-scale warmings are accompanied by increases in atmospheric carbon dioxide with a global-scale impact (Schulz et al. 1999).

We summarize some numerical experiments when freshwater forcing or idealised background conditions are changed, which are helpful to explore the phase space of the complex dynamics of the climate system, especially during the last termination where abrupt changes are detected. It is also important to understand past warm climate states where models show a mismatch with data, e.g., for the Holocene (Lohmann et al. 2013, Liu et al. 2014, Lohmann 2016) or the Pliocene (Salzmann et al. 2013).

## METHODS

### *Model of intermediate complexity*

The three-dimensional ocean model is based on the large-scale geostrophic model (LSG, Maier-Reimer et al. 1993), which is part of the Bremen Earth System Model of intermediate complexity (Lohmann et al. 2003, Butzin et al. 2005, Knorr & Lohmann 2007). The horizontal resolution is 3.5° on a semi-staggered grid with 11 levels in the vertical. It includes a simple thermodynamic sea-ice model, a 3rd order advection scheme for temperature and salinity (Schäfer-Neth & Paul 2001) and a parameterisation of overflow (Lohmann 1998). The ocean is driven by monthly fields of wind stress, surface air temperature and freshwater flux, which are taken from a present day and Last Glacial Maximum (LGM) simulation of the atmospheric general circulation model ECHAM3 / T42 (Lohmann & Lorenz 2000, Roeckner et al. 1992). In order to close the hydrological cycle, a run-off scheme transports freshwater from the continents to the ocean. We employ a modelling approach, which allows an adjustment of surface temperatures and salinity to changes in the ocean circulation, based on an atmospheric energy balance model (Lohmann et al. 1996, Prange et al. 2003). The model (abbreviated as EBM-LSG in the following) belongs to the models of intermediate complexity (Claussen et al. 2002) and has been applied to glacial climate dynamics (Prange et al. 2002, 2004, Romanova et al. 2004, Knorr & Lohmann 2003, Knorr 2005, Knorr & Lohmann 2007), carbon isotopes (Butzin et al. 2005, Hesse et al. 2011, Butzin et al. 2012) and the Cenozoic climate (Butzin et al. 2011, Lohmann et al. 2015).

### *Comprehensive Earth System Model*

We use a comprehensive fully coupled Earth System Model, COSMOS (ECHAM5-JSBACH-MPIOM) for this study. The atmospheric model ECHAM5 (Roeckner et al. 2003), complemented by a land-surface component JSBACH (Brovkin et al. 2009), is used at T31 resolution (~3.75°), with 19 vertical layers. The ocean model MPI-OM (Marsland et al. 2003), including sea-ice dynamics that is formulated using viscous-plastic rheology, has a resolution of GR30 (3° × 1.8°) in the horizontal, with 40 uneven distributed vertical layers. The climate model has already been used to simulate the last millennium (Jungclaus et al. 2010), internal climate variability (Wei et al. 2012), the Miocene warm climate (Knorr et al. 2011, Knorr & Lohmann 2014), the Pliocene (Stepanek & Lohmann 2012, Haywood et al. 2013), Holocene variability and trends (Wei & Lohmann 2012, Varma et al. 2012, Lohmann et al. 2013), the last interglacial (Lunt et al. 2013, Bakker et al. 2014, Felis et al. 2015, Pfeiffer & Lohmann 2016, Sutter et al. 2016), and the LGM climate (Zhang et al. 2013, 2014, Gong et al. 2015, Stärz et al. 2016), including hosing experiments (Kageyama et al. 2012, Gong et al. 2013). The model has recently been coupled to an ice-sheet model (Barbi et al. 2014, Gierz et al. 2015) and is enhanced with water-isotope modules (Werner et al. 2011, Langebroek et al. 2011, Xu et al. 2012, Haese et al. 2013, Dietrich et al. 2013, Goelles et al. 2014, Werner et al. 2015, Sutter et al. 2015). For another recent application of this model, see Stepanek & Lohmann 2016.

## DEGLACIAL WARMING INDUCES AN ABRUPT AMOC TRANSITION: EBM-LSG EXPERIMENTS

The experiments with the EBM-LSG consist of two major parts. In the first part we simulate the deglacial climate between about 20 ka and the onset of the Bølling/Allerød (B/A) warm phase (experiments B1-B4). These experiments are identical to the ones published in Knorr & Lohmann (2007). Deglacial warming is implemented by a transition from glacial to interglacial background climate being accomplished within 15 ka. The background climate is provided by monthly fields of air temperature, sea ice (Southern Hemisphere) and wind stress, linearly interpolated between the LGM conditions at 20 ka before present and present day climatology (cf. Fig. 1a). We see how the linear warming of the background climate boundary conditions can induce a rapid intensification of the ocean circulation (Fig. 1a, b). The basic mechanism is related to a release of convectively unstable warm subsurface water in the northern North Atlantic.

The water gets vertically unstable due to changes in surface warming and sea-ice retreat. The warm subsurface water during weak overturning is released and provides a heat flush in the northern North Atlantic. This heat flush is related to the B/A transition as seen in ice cores. A similar mechanism of subsurface heat release is described in Knorr & Lohmann (2007), Kim et al. (2012), and Gong et al. (2013). The vertical structure can even be used to detect ocean circulation changes (Rühlemann et al. 2004, Lohmann et al. 2008).

In the second part of experiments attention is paid to investigating the effect of MWP-1A (deglacial melt water pulse 1A) on the AMOC and to evaluating its impact on the B/A and the subsequent deglacial meltwater. These freshwater perturbation experiments are denoted as MWP1–MWP5 (Fig. 2) and represent additional simulations to the experiments (B1-B4).

All meltwater discharge to the North Atlantic is uniformly applied between 20°N and 50°N. The timing and amplitude of the freshwater perturbations is depicted in Figure 2a. Figure 2a,b emphasizes the combined effect of hosing and AMOC strengthening due to global warming. The hosing provides only a second-order effect, modulating the timing of the transition. In MWP1, the release of the MPW-1A to the North Atlantic delays the abrupt AMOC amplification by about one decade, but does not inhibit the amplification of the AMOC. The rising freshwater flux of MWP-1A causes a drop back to

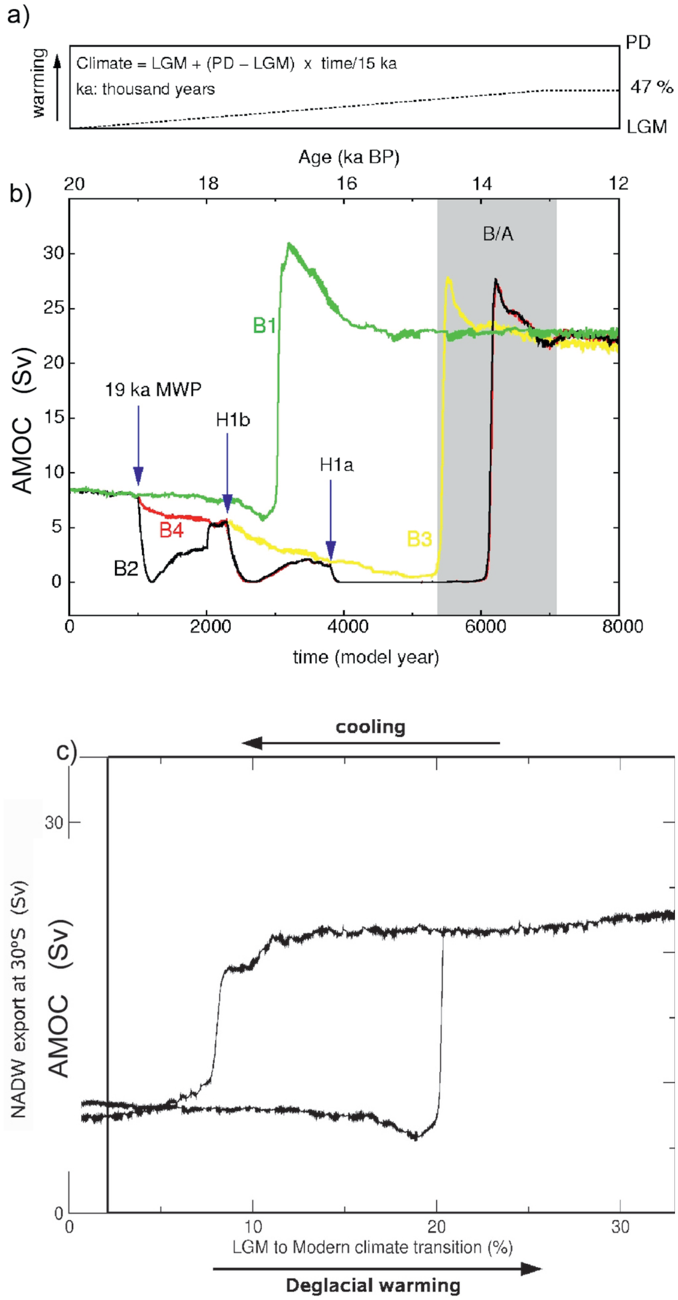


**Fig. 1:** a): Prescribed temporal changes in the global background climate and simulated Atlantic Meridional Overturning Circulation (AMOC) changes with the model of intermediate complexity. The background climate conditions are linearly interpolated between glacial and modern conditions. All experiments start from the glacial equilibrium and the gradual warming is stopped after 7000 model years. b): Green curve (B1) represents the experiment without any deglacial freshwater pulses. Experiments B2 (black curve), B3 (yellow curve), and B4 (red curve) exhibit different successions of deglacial meltwater pulse scenarios to the North Atlantic. The beginning of the respective freshwater perturbation is indicated by the blue arrows. c): Hysteresis diagram based on B1. The AMOC index is calculated from the export at 30°S in the Atlantic Ocean.

**Abb. 1:** (a): Vorgeschriebene zeitliche Veränderungen im globalen Hintergrundklima und simulierte AMOC (Atlantic Meridional Overturning Circulation) im EBM-LSG Modell mittlerer Komplexität. Die Hintergrundklimabedingungen werden linear zwischen Eiszeit und modernen Bedingungen interpoliert. Diese schrittweise Erwärmung wird nach 7000 Modelljahren gestoppt. b): Die grüne Kurve (B1) stellt das Experiment ohne deglaziales Süßwasser dar. Experimente B2 (schwarze Kurve), B3 (gelbe Kurve) und B4 (rote Kurve) weisen unterschiedliche Abfolgen von deglazialen Schmelzwasserpulsen aus. Der Beginn der jeweiligen Süßwasserstörungen wird durch die blauen Pfeile angezeigt. c): Hysterese Diagramm bezogen auf B1. Der AMOC Index wurde über den Wassermassenexport bei 30°S berechnet.

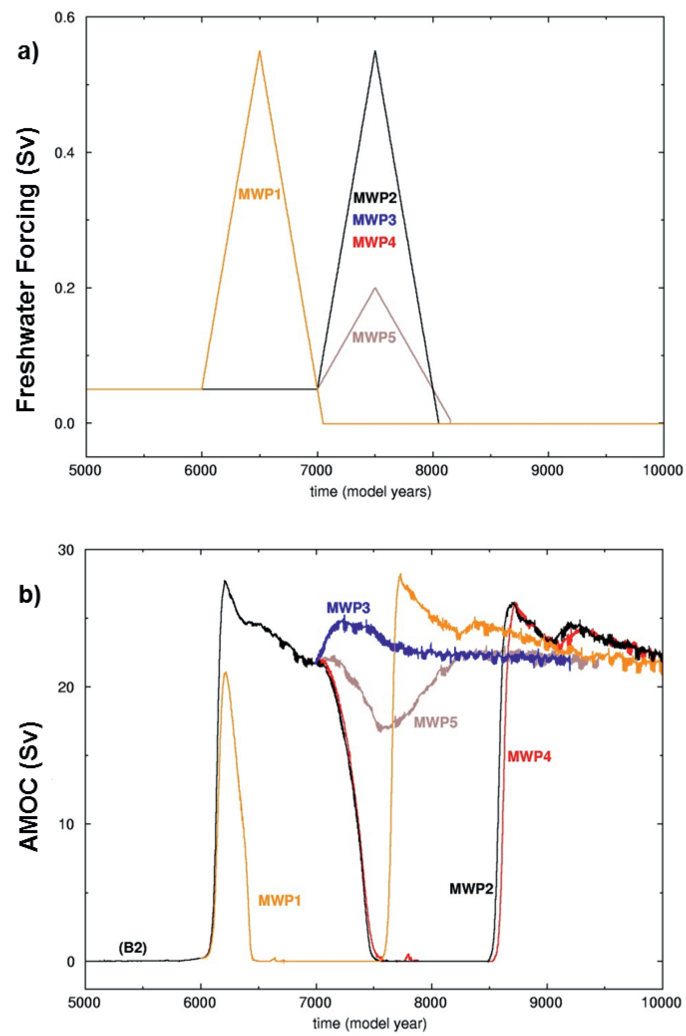


**Fig. 2:** a): Different deglacial hosing experiments with different timing and amplitude in the model of intermediate complexity. In experiment MWP1, the onset of the meltwater MWP-1A is after 6000 years prior to the onset of the Bølling/Allerød (B/A) in B2. In experiments MWP2-MWP5, MWP-1A is discharged after 7000 model years. In MWP2 and MWP3, it is released to the North Atlantic and the Weddell Sea, respectively. In MWP4 and MWP5 the pulses are discharged uniformly to both locations. b): Temporal signature of the AMOC (Atlantic Meridional Overturning Circulation) with respect to different meltwater scenarios with B2 as the base experiment (cf. Fig. 1b).

**Abb. 2:** a): Unterschiedliche deglaziale Experimente mit verschiedenen Süßwasserstörungen im EBM-LSG Modell mittlerer Komplexität. Im Experiment MWP1 wird der Schmelzwasserpulses 6000 Jahre vor den Beginn des Bølling/Allerød gelegt. In den Experimenten MWP2-MWP5 wird der Beginn des Schmelzwasserpulses nach 7000 Modelljahren realisiert. In MWP2 und MWP3 wird das Süßwasser im Norden bzw. im Süden eingebracht. Hingegen werden in den Experimenten MWP4 und MWP5 das Süßwasser zu gleichen Teilen in den Norden und Süden eingebracht. b): Zeitlicher Verlauf von AMOC (Atlantic Meridional Overturning Circulation) unter den verschiedenen Schmelzwasserszenarien mit B2 als Basisexperiment, welches auch in Abb. 1b gezeigt wird.

the "off-mode" simultaneously to the maximum meltwater magnitude. The AMOC remains stalled until the warming proceeds to more than 50 % of the total termination-I warming at 7500 years. In experiment MWP2, the MWP-1A is released 1000 years later than in MWP1 and the AMOC is also suppressed to the "off-mode", and the recovery to an interstadial AMOC occurs 500 years after the cessation of MWP-1A within a century. The application of MWP-1A only in the Weddell Sea results in a slight increase of the AMOC in experiment MWP3. The division of the meltwater inflow to both, the North Atlantic and the Weddell Sea region in MWP4 also ceases AMOC for about 1000 years with a minimal retarded model response compared to MWP2. The application of a weaker meltwater pulse than in MWP4 temporarily reduces, but does not shut down the AMOC in MWP5.

Again, the deglacial resumption of the AMOC is associated with heat release from the sub-surface ocean in the North Atlantic, as well as large-scale salinity advection of near-surface waters from the South Atlantic/Indian Ocean and the tropics to the formation areas of North Atlantic deep water. The restarted AMOC possesses a strong insensitivity to deglacial meltwater pulses (Figs. 1b, 2b), and coexistent, a distinct bistability in the hysteresis curve for cumulative positive freshwater fluxes to the North Atlantic (Fig. 1).

## NORTHERN AND SOUTHERN HOSING AND OVERSHOOT IN THE AMOC IN COSMOS

A quite different concept for deglacial AMOC changes (compared to the previous section) is that a reduction of deglacial meltwater may induce a Northern Hemisphere warming after the meltwater has stopped (e.g., Liu et al. 2009, Gong et al. 2013, Zhang et al. 2013). In our COSMOS model integrations, a freshwater hosing of 0.2 Sv (1 Sv = $10^6$ $m^3/s$) has been applied for 150 years in the North Atlantic (NA) in the ice-rafted debris (IRD) belt in the North Atlantic Ocean (40°N - 55°N) or in the Southern Ocean (SO) in the region (52° - 62°S, 40°W - 62°W), respectively (Fig. 3). The experiments LGM ctl and the North Atlantic hosing (LGM NA 0.2 Sv) have been used in Zhang et al. (2013).

The NA hosing experiments indicate an AMOC reduction, but the following recovery stages after 250 years exhibit a clear overshoot (Fig. 3a). One can subdivide the underlying dynamics of the overall recovery into two stages: one directly following the end of the freshwater perturbation that describes the initial resumption, and a superposed phase that coincides with the AMOC overshoot dynamics (Gong et al. 2013, Zhang et al. 2013): The deep-water formation in the South Labrador Sea reduces to 4-7 Sv, and a shutdown of deep-water formation in the Greenland-Iceland-Norwegian (GIN) Seas is diagnosed. Subsequently, an instant restart of deep-water formation in the South Labrador Sea is triggered, whereas the restart in the GIN Seas occurs 30 years later. The corresponding trigger mechanism is related to a modified salinity stratification and subsurface warming that quickly build up during the freshwater perturbation. The surface anomaly in surface temperature is shown in Figure 3b.

The SO hosing provides almost no change in AMOC (Fig. 3a, blue line), and the surface temperature signature shows only a minor cooling after 150 years in the North Atlantic (not shown).

## INFLUENCE OF $CO_2$ AND NORTHERN HEMISPHERE ICE-SHEET HEIGHT

Here, we investigate the role of $CO_2$ changes on AMOC during times of intermediate glacial ice volume using COSMOS. Following Zhang et al. (2014), we perform a transient simulation in which we linearly increase atmospheric $CO_2$ concentration from 185 to 205 ppm within 500 years, under an intermediate ice-sheet height (40 % of the LGM ice-sheet level; Fig. 4a). Figure 4b indicates an abrupt onset of AMOC along the linear increase in $CO_2$ and thus surface temperature in the North Atlantic (Fig. 4c). The surface temperature

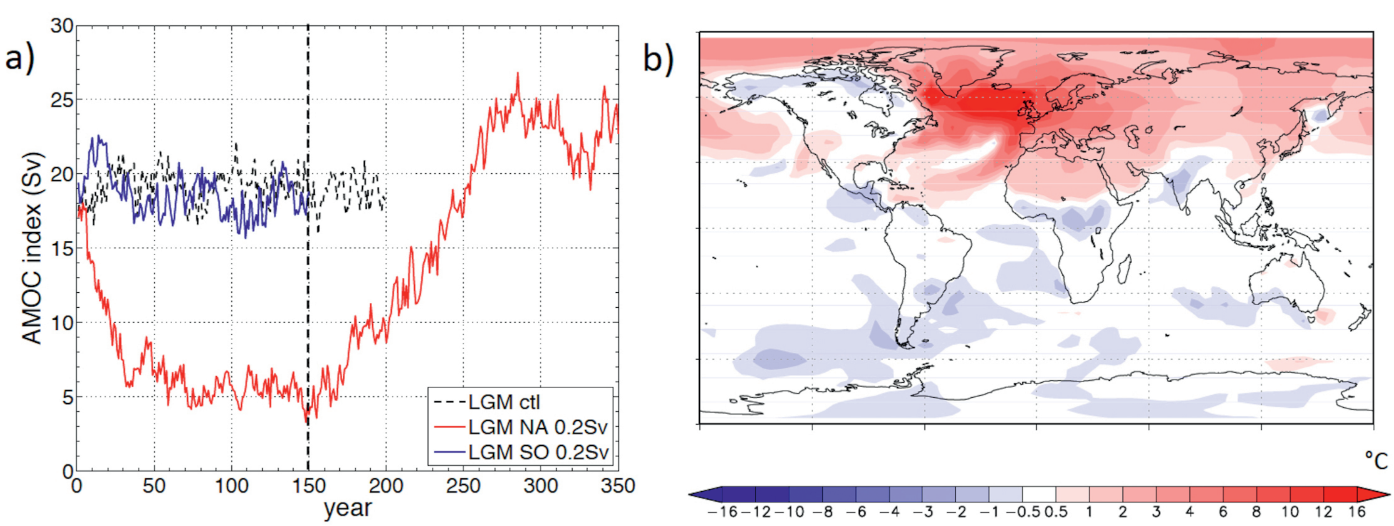


**Fig. 3:** Earth system model COSMOS experiments. a): AMOC response to freshwater hosing of 0.2 Sv in the North Atlantic Ocean (NA) or in Southern Ocean (SO), respectively. b): The NA hosing experiment indicates an AMOC reduction, but the following recovery stages after 250 years exhibit a clear overshoot.

**Abb. 3:** Experimente mit dem Erdsystemmodell COSMOS. a): AMOC Reaktion auf Süßwasserstörung von 0,2 Sv im Nordatlantik (NA) oder im Südlichen Ozean (SO). b): Das NA Experiment zeigt eine AMOC-Reduktion, aber die folgende Erholung nach 250 Jahren zeigt einen Überschwinger in der Atlantic Meridional Overturning Circulation (AMOC).

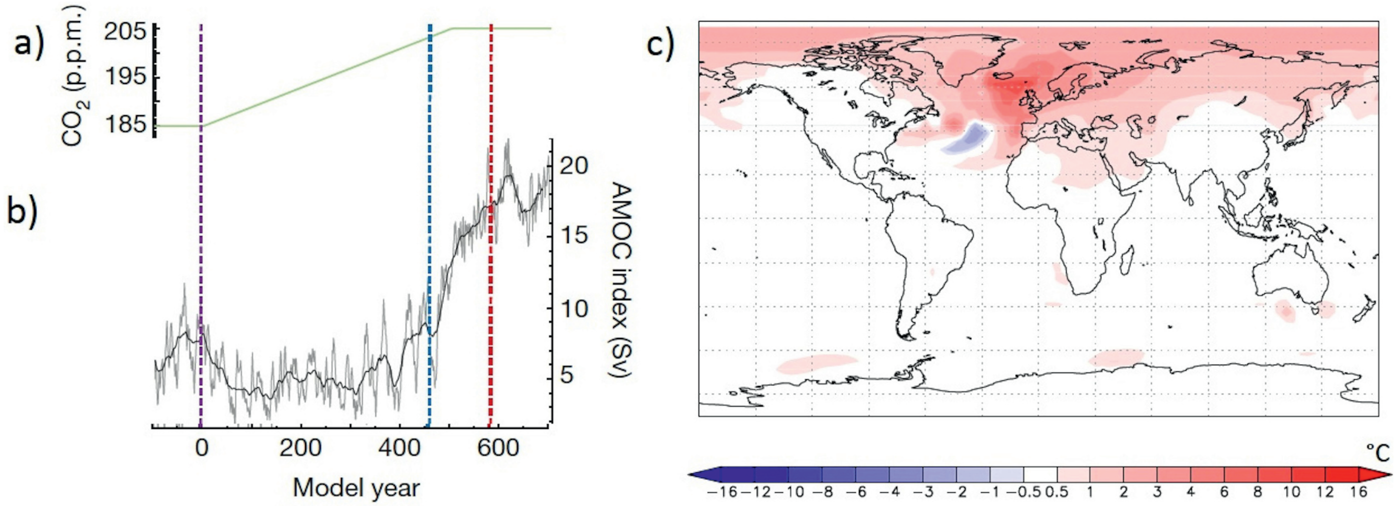


**Fig. 4:** Earth system model COSMOS experiments. a): Transient $CO_2$ forcing. b): Atlantic Meridional Overturning Circulation (AMOC) response. Bold lines show the 30-year running mean of the original data (grey lines). The vertical purple, blue and red dotted lines represent the starting points for the transient simulations, abrupt AMOC transitions and cooling in the Southern Hemisphere, respectively. Negative model years indicate the control simulation of a glacial state, but with 40 % Northern Hemisphere ice-sheet height, which is close to the height threshold. c): Surface temperature anomaly between year 600–700 (warming) and 300–400 (cooling) of panel 4b.

**Abb. 4:** Experimente mit dem Erdsystemmodell COSMOS. a): Transienter $CO_2$-Antrieb. b): Antwort der Atlantic Meridional Overturning Circulation (AMOC). Dicke Linien zeigen das 30-Jahresmittel der Originaldaten (graue Linien). Die vertikalen lila, blau und rot gestrichelten Linien stellen die Ausgangspunkte für die transiente Simulationen. Negative Modelljahre stehen für die Kontrollsimulation eines eiszeitlichen Zustands, der mit 40 % der Eisdeckenhöhe gerechnet wurde. 40 % ist in der Nähe der Schwelle der kritischen Eisschildhöhe. c): Oberflächen-Temperaturanomalie zwischen Jahr 600–700 (Erwärmung) und 300–400 (Abkühlung) bezogen auf Abb. 4 b.

in Figure 4c is shown as anomaly between the model year 600–700 (warming) and 300–400 (cooling) in this simulation (Fig. 4b). The response can be understood in terms of a transition in a bistable system with respect to the ice-sheet height (Zhang et al. 2014).

## INFLUENCE OF STRONG SOUTHERN HOSING, $CO_2$, AND ORBITAL FORCING

Additional hypotheses related to Southern Hemisphere hosing from the Antarctic Ice Sheet (AIS) and warming are tested for deglaciation using COSMOS. The $CO_2$ and freshwater history used to force our transient runs is shown in Figure 5. The $CO_2$ concentration is fixed to LGM level (i.e. 185 ppm) before 18 ka BP. After that, the Antactic ice core EDC $CO_2$ record is imposed to force our transient simulations (Fig. 5a). Freshwater enters into the Southern Ocean (SO) where the freshwater input is linearly scaled by reconstructed marine records of iceberg-rafted debris (Weber et al. 2014). The freshwater forcing is determined by assuming that 50 % of the maximum sea-level rates during MWP-1A (40 mm/year) originated from Antarctica. The corresponding peak freshwater forcing around Antarctica is shown in Figure 5b. Because of the above mentioned sea-level assumption and the fact that we have to use the acceleration factor 5 for the transient integrations, the actual freshwater forcing is 5 times larger per time step than in runs without acceleration. The model runs were performed with COSMOS and the basic runs were published in Weber et al. (2014). Here, we present some analyses of the long-term climate scenarios.

Finally, we employed the transient orbital forcing in the experiments. The annual mean orbital forcing is due to obliquity (precession cancels out for the annual mean forcing) and is displayed in Figure 5c. As a caveat of our methodology due to computational resources, our runs were accelerated by factor 5 (cf. Lorenz & Lohmann 2004), implying the simulated warming and hosing in our runs might not directly represent the real Bølling warming and mechanisms of local freshwater input (e.g., Lunt et al. 2006, Timm & Timmermann 2007).

To determine the effect of different freshwater sources, three transient freshwater forcing experiments were conducted under glacial background conditions (Fig. 6). Freshwater flux is added to the coastal areas of the East Antarctic Ice Sheet (EAIS) (0° - 180°E) and the West Antarctic Ice Sheet (WAIS) (120°W - 60°W). In DG1, the forcing is assumed to originate from the EAIS. In DG2, EAIS (WAIS) forcing is used for the period 21–15 ka (15–14 ka). DG3 assumes EAIS forcing at 21–16 ka and WAIS forcing at 16–14 ka. Two other experiments (DG2C and DG2CO) were conducted to examine the effect of $CO_2$ (DG2C) as well as a combination of $CO_2$ and orbital forcing (DG2CO) on AMOC and surface temperature. DG2C and DG2CO show almost the same signature in time and space, indicating that the $CO_2$ effect is stronger than the effect by insolation.

Figures 6d, 6e show the surface temperature anomaly between 14.7-14.6 ka (warming in the north) and 15.55-15.4 ka (cooling in the north) in simulations DG2 and DG2CO. This bipolar seesaw is related to an AMOC increase (Fig. 6c). The SO meltwater pulse weakens the AMOC strength after a delay of 100 years when the large freshwater signal is transported to the North Atlantic. The AMOC increase and the related warming over Greenland after 14.7 ka are thus not due to the simultaneous SO meltwater pulse, but to a weakened SO freshwater forcing prior to this time (Fig. 5b).

For the water surrounding Antarctica, Weber et al. (2014) found a more pronounced halocline during periods of

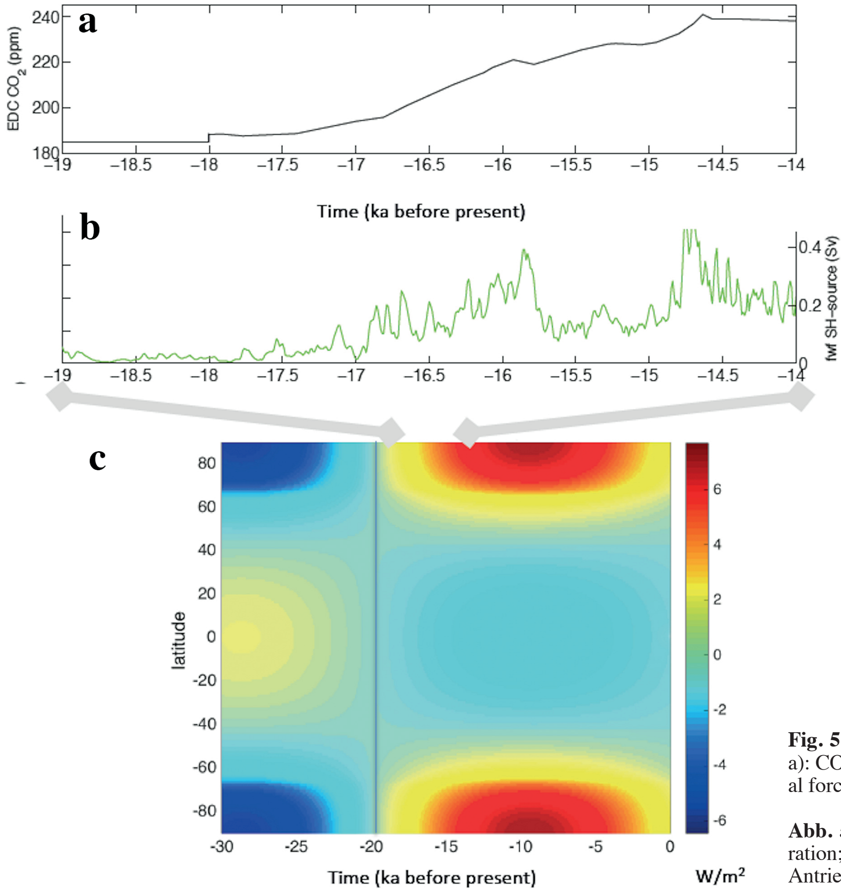


**Fig. 5:** Forcing for the Earth system model COSMOS experiments. a): $CO_2$ concentrations; b): Southern Ocean freshwater flux; c): orbital forcing (only annual mean is displayed).

**Abb. 5:** Antrieb für Erdsystemmodell COSMOS. a): $CO_2$-Konzentration; b): Deglaziales Süßwasser im Südlichen Ozean; c): orbitaler Antrieb für das jahreszeitlich gemittelte Signal.

strong freshwater forcing as the main cause for the subsurface warming in the SO during deglaciation. Such subsurface warming may have induced instabilities in the coupled atmosphere-ocean-ice system, which could be important for ice-shelf instabilities and shall be investigated in the future.

We furthermore mention that our models (COSMOS and EBM-LSG) show different full glacial overturning rates. For the EBM-LSG model, we validated the circulation model with carbon isotope data (Hesse et al. 2011) and find a good agreement with a stronger overturning circulation as used here as the LGM control state. A shallower than today circulation with about modern circulation strength is consistent with the carbon isotope data (Hesse et al. 2011). Zhang et al. (2013, 2014) compared the deep water and surface signatures in COSMOS with proxy data and found a general agreement with paleoclimate evidences (e.g., a salty and cold Antarctic Bottom Water).

## DISCUSSION AND CONCLUSIONS

Our model experiments reveal insights for the Bølling/Allerød (B/A) North Atlantic interstadial dynamics and the impact of deglacial meltwater pulses. Robust features seem to be:

- Deglacial global warming induces stronger AMOC (Figs. 1b, 4b). If the system is in a bistable window, a linear forcing can yield non-linear AMOC changes (Fig. 1b, Fig. 2b, Fig. 4b). An abrupt onset of the AMOC can be triggered by a gradual global warming during deglaciation showing typical hysteresis behaviour (Fig. 1c). The intensification depends on its glacial mean state (Knorr & Lohmann 2007), and this intensification is opposite to the weakening response of AMOC to increased $CO_2$, starting from the present to the future scenarios (e.g., Lohmann et al. 2008). This dependence of the background state is caused by the large area of sea-ice cover under glacial conditions (Zhu et al. 2015). Northern Hemisphere freshwater hosing can affect the timing of the AMOC onset.

- Northern Hemisphere freshwater hosing weakens AMOC with a potential temperature and AMOC overshoot response after the freshwater forcing has stopped (Fig. 3a,b). However, the overshoot is just a transient phenomenon. Therefore, it cannot explain the B/A dynamics alone.

- Hosing in the Southern Hemisphere has a small effect on the AMOC if the perturbation is in the order of the Northern Hemisphere signal (Figs. 2b, 3a). This is in contrast to the findings of Weaver et al. (2003), using a model of intermediate complexity – see also Kerr 2003 and Stocker 2003 for a discussion of southern and northern forcing. In our case the EBM-LSG shows a slight increase in AMOC due to a Southern Hemisphere signal (MWP3 in Fig. 2).

- If the Southern Hemisphere freshwater flux is strongly enhanced – in our case to mimic the possible sea-level contribution in the COSMOS run – it can affect the AMOC. An increase in AMOC and warming over Greenland can be simulated either by ending freshwater forcing in the Northern Hemisphere (Fig. 3) or as a delayed response to a weakened

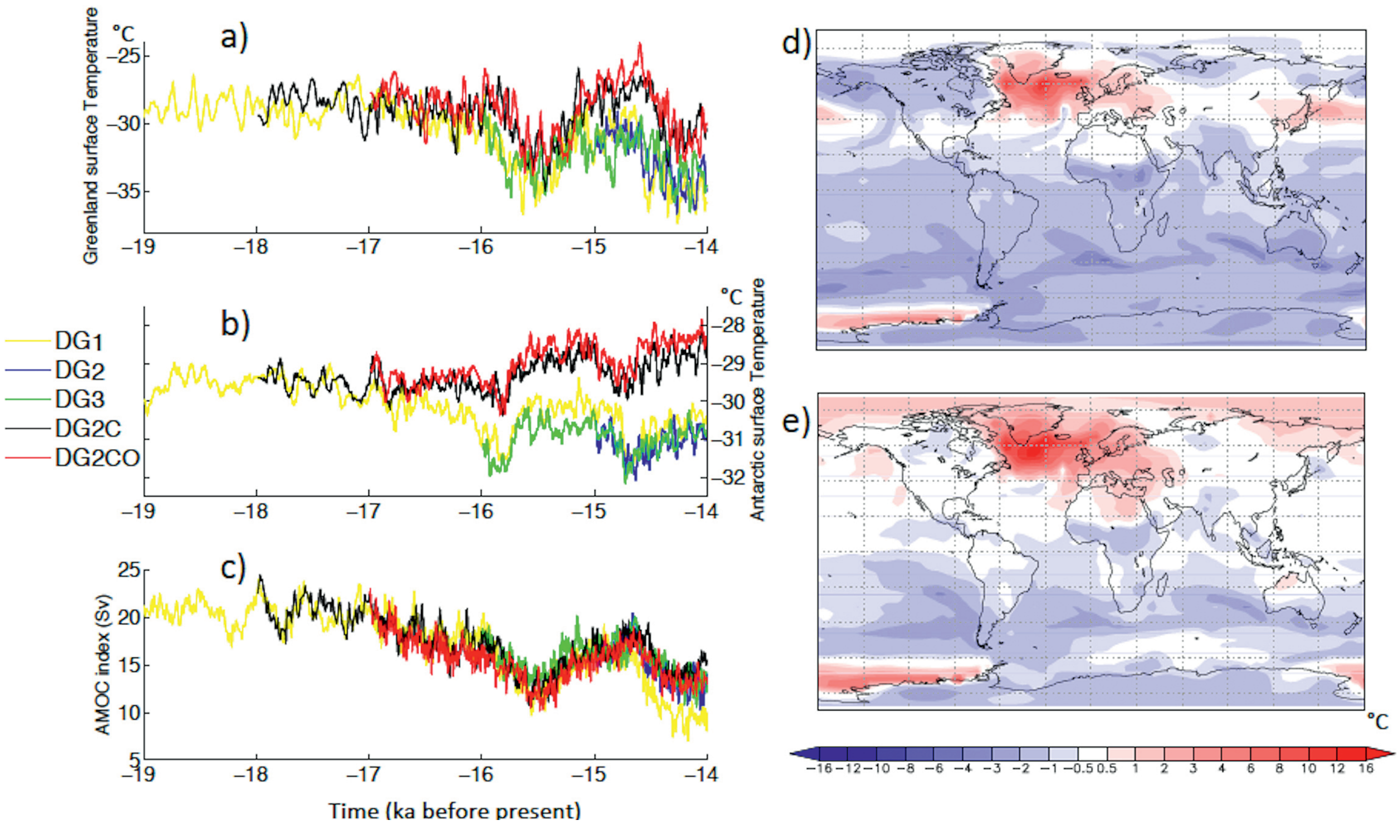


**Fig. 6:** Earth system model COSMOS experiments. a): History of original freshwater flux to the Southern Ocean. b) and c): Temperature and Atlantic Meridional Overturning Circulation (AMOC) response to external forcing. DG1: the freshwater forcing is assumed to originate from the East AIS. DG2: East (West) AIS forcing is used for the period 21–15 ka (15–14 ka). DG3: East AIS forcing at 21–16 ka and West AIS forcing at 16–14 ka. In DG2C, varied $CO_2$-concentrations were prescribed for the period 18–14ka. Orbital forcing covering the period from 17–14 ka were additionally used in DG2CO. d and e): show the surface temperature anomalies between 14.7–14.6 ka and 15.55-15.4 ka in simulations DG2 in (d) and DG2CO in (e), respectively.

**Abb. 6:** Experimente mit dem Erdsystemmodell COSMOS. a) Historie des originalen Süßwasserflusses im südlichen Ozean; b) und c): Temperaturantwort und Reaktion der Atlantic Meridional Overturning Circulation (AMOC) auf externe Randbedingungen. Verschiedene Szenarien DG1: Süßwasser stammt aus dem östlichen AIS. DG2: Östliches Süßwasser für den Zeitraum 21–15 ka, westliches für 15-14 ka. DG3: Östliches Süßwasser für 21–16 ka und westliches für 16–14 ka. In DG2C werden die $CO_2$-Konzentrationen für den Zeitraum 18–14 ka angenommen. Zusätzlich in DG2CO: Orbitaler Antrieb für 17–14 ka. Tafeln d und e) zeigen die Oberflächentemperatur-Anomalien zwischen 14,7–14,6 ka und 15,55–15,4 ka in Simulationen DG2 (6d) beziehungsweise DG2CO in (6e).

freshwater forcing in the Southern Hemisphere (Fig. 5, 6). Our finding is consistent with Swingedouw et al. (2009). They proposed the hypothesis that a SO freshwater pulse can impact the strength of the AMOC only when the amount of freshwater is larger than a certain value.

- Larger glacial Northern Hemisphere ice-sheet height produces stronger AMOC. The ice-sheet height seems to be an important parameter for multiple equilibria of the AMOC and possibly millenial variability at intermediate ice-sheet height. If the AMOC is in this bistable window, other parameters like $CO_2$ can cause abrupt transitions (Fig. 4). We speculate that for the termination, the change in ice-sheet height is most likely a second-order effect since the lowering of the Northern Hemisphere ice sheet will weaken the AMOC.

Using different types of models, it is important to explore the phase space of abrupt climate changes like the deglaciation, and to explore the separation between first and second order effects (Lohmann 2009). Several regional features like the subsurface warming (e.g., Rühlemann et al. 2004, Weber et al. 2014), seasonal sea-ice cover (Abelmann et al. 2015), and subsequent effects shall be studied, using different models with different levels of complexity. For example, in the intermediate complexity model EBM-LSG and the full AOGCM COSMOS, a smooth warming can produce an abrupt change of AMOC, while in Zhu et al. (2015) the AMOC intensification seems to be more gradual in their AOGCM. The change of AMOC in consequence to changes in ice-sheet height (higher ice sheet leads to stronger AMOC) is also qualitatively consistent with the finding in another fully coupled climate model in the sense that lowering the ice sheet reduces AMOC (Zhu et al. 2014). It is concluded that model experiments under different forcings (including single forcing experiments) are required for a wide range in the phase space of solutions.

Some general questions remain. As yet, it is not clear if the exact timing of transtions is partly phase-locked to an oscillating system (as seen e.g., in Winton 1993, Wang & Mysak 2006, Schulz et al. 1999, Kim et al. 2012), if the transitions are solely triggered by external forcing like freshwater or deglacial warming (Knorr & Lohmann 2007, Liu et al. 2009), or if noise-induced transitions play a role (e.g., Timmermann & Lohmann 2000). Others than oceanic processes can induce part of the long-term signal through modulations of atmospheric teleconnections and atmospheric bridges (Rodgers et al. 2003, Lohmann, 2016). All the different concepts and their underlying assumptions might need to be revisited and to be carefully compared to paleoclimate proxy data. However, a further major difficulty for the validation of model results is the interpretation of the recorder systems since the paleodata may be biased towards different seasons or other recorder-related conditions (e.g., Laepple et al. 2011, Lohmann & Wiltshire 2012, Lohmann et al. 2013, Hesse et al. 2014, Werner et al. 2015, Pfeiffer & Lohmann 2016), providing a source of uncertainty of forcing mechanisms and long-term climate variability.

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*References*

*Abelmann, A., Gersonde, R., Knorr, G., Zhang, X., Chapligin, B., Maier, E., Esper, O., Friedrichsen, H., Lohmann, G, Meyer, H. & Tiedemann, R.* (2015): The seasonal sea ice zone in the glacial Southern Ocean as a carbon sink.- Nature comm. 6, 8136. doi: 10.1038/ncomms9136.

*Bakker, P., Masson-Delmotte, V., Martrat, B., Charbit, S., Renssen, H. Groger, M., Krebs-Kanzow, U., Lohmann, G., Lunt, D.J., Pfeiffer, M., Phipps, S.J., Prange, M., Ritz, S.P., Schulz, M., Stenni, B., Stone, E.J. & Varma, V.* (2014): Temperature trends during the Present and Last interglacial periods - A multi-model-data comparison.- Quat. Sci. Rev. 99: 224-243, doi:10.1016/j.quascirev.2014.06.031.

*Barbi, D., Lohmann, G., Grosfeld, K. & Thoma, M.* (2014): Ice sheet dynamics within an Earth system model: coupling and first results on ice stability and ocean circulation.- Geosci. Model Dev. 7: 2003-2013, doi:10.5194/gmd-7-2003-2014.

*Bender, M.L., Malaize, B., Orchardo, J., Sowers, T. & Jouzel, J.* (1999): High precision correlations of Greenland and Antarctic ice core records over the last 100 kyr.- In: P.U. CLARK, R.S. WEBB, & L.D. KEIGWIN (eds): Mechanisms of global climate change at millennial time scales. Geophys. Monogr. 112: 149-164.

*Brovkin, V., Raddatz, T., Reick, C.H., Claussen, M. & Gayler, V.* (2009): Global biogeophysical interactions between forest and climate.- Geophys. Res. Lett. 36: 1-5.

*Butzin, M., Prange, M. & Lohmann, G.* (2005): Radiocarbon simulations for the glacial ocean: the effects of wind stress, Southern Ocean sea ice and Heinrich events.- Earth Planet. Sci. Lett. 235: 45-61, doi: 10.1016/j.epsl.2005.03.003.

*Butzin, M., Lohmann, G. & Bickert, T.* (2011): Miocene ocean circulation inferred from marine carbon cycle modeling combined with benthic isotope records.- Paleoceanography 26: PA1203, doi: 10.1029/2009PA001901.

*Butzin, M., Prange, M. & Lohmann, G.* (2012): Readjustment of glacial radiocarbon chronologies by self-consistent three-dimensional ocean circulation modeling.- Earth Planet. Sci. Lett. 317-318: 177-184, doi: 10.1016/j.epsl.2011.11.046

*Claussen, M., Mysak, L.A., Weaver, A.J., Crucifix, M., Fichefet, T., Loutre, M.-F., Weber, S.L., Alcamo, J., Alexeev, V.A., Berger, A., Calov, R., Ganopolski, A., Goosse, H., Lohmann, G., Lunkeit, F., Mokhov, I.I., Petoukhov, V., Stone, P. & Wang, Z.* (2002): Earth System Models of intermediate complexity: closing the gap in the spectrum of Climate System Models.- Clim. Dyn. 18: 579-586.

*Dietrich, S., Werner, M., Spangehl, T. & Lohmann, G.* (2013): Influence of orbital forcing and solar activity on water isotopes in precipitation during the mid and late Holocene.- Clim. Past 9: 13-26, doi: 10.5194/cp-9-13-2013.

*Crowley, T.J.* (1992): North Atlantic deep water cools the southern hemisphere.- Paleoceanography 7: 489-497.

*Felis, T., Giry, C., Scholz, D., Lohmann, G., Pfeiffer, M., Pätzold, J., Kölling, M. & Scheffers, S.R.* (2015): Tropical Atlantic temperature seasonality at the end of the last interglacial.- Nature Comm. 6: 6159, doi: 10.1038/ncomms7159.

*Flohn, H.* (1986): Singular events and catastrophes now and in climatic history.- Naturwissenschaften 73: 136-149.

*Ganopolski, A. & Rahmstorf, S.* (2001): Rapid changes of glacial climate simulated in a coupled climate model.- Nature 409: 153-158.

*Gierz, P., Lohmann, G. & Wei, W.* (2015): Response of Atlantic overturning to future warming in a coupled atmosphere – ocean – ice-sheet model.- Geophys. Res. Lett. 42, doi: 10.1002/2015GL065276.

*Goelles, T., Grosfeld, K. & Lohmann, G.* (2014): Semi-Lagrangian transport of oxygen isotopes in polythermal ice sheets: implementation and first results.- Geosci. Model Dev. 7: 1395-1408, doi: 10.5194/gmd-7-1395-2014.

*Gong, X., Knorr, G., Lohmann, G. & Zhang, X.* (2013): Dependence of abrupt Atlantic meridional ocean circulation changes on climate background states.- Geophys. Res. Lett. 40: 3698-3704, doi: 10.1002/grl.5070.1.

*Gong, X., Zhang, X., Lohmann, G., Wei, W., Zhang, X. & Pfeiffer, M.* (2015): Higher Laurentide and Greenland ice sheets strengthen the North Atlantic Ocean circulation.- Clim. Dyn. 45: 139-150, doi: 10.1007/s00382-015-2502-8,

*Haese, B., Werner, M. & Lohmann, G.* (2013): Stable water isotopes in the coupled atmosphere-land surface model ECHAM5-JSBACH.- Geosci. Model Dev. 6: 1463-1480, doi: 10.5194/gmd-6-1463-2013.

*Haywood, A.M., Hill, D.J., Dolan, A.M., Otto-Bliesner, B., Bragg, F., Chan, W.-L., Chandler, M.A., Contoux, C., Jost, A., Kamae, Y., Lohmann, G., Lunt, D.J., Abe-Ouchi, A., Pickering, S.J., Ramstein, G., Rosenbloom, N. A., Sohl, L., Stepanek, C., Yan, Q., Ueda, H. & Zhang, Z.* (2013): Large-scale features of Pliocene climate: results from the Pliocene Model Intercomparison Project.- Clim. Past, 9: 191-209, doi: 10.5194/cp-9-191-2013.

*Hesse, T., Butzin, M., Bickert, T. & Lohmann, G.* (2011): A model-data comparison of δ13C in the glacial Atlantic Ocean.- Paleoceanography 26: PA3220, doi: 10.1029/2010PA002085.

*Hesse, T., Wolf-Gladrow, D., Lohmann, G., Bijma, J., Mackensen, A. & Zeebe, R.E.* (2014): Modelling $\delta^{13}C$ in benthic foraminifera: insights from model sensitivity experiments.- Marine Micropal. 112: 50-61. DOI: 10.1016/j.marmicro.2014.08.001.

*Jungclaus, J.H. Lorenz, S.J., Timmreck, C., Reick, C.H., Brovkin, V., Six, K., Segschneider, J., Giorgetta, M.A., Crowley, T.J., Pongratz, J., Krivova, N.A., Vieira, L.E., Solanki, S.K., Klocke, D., Botzet, M., Esch, M., Gayler, V., Haak, H., Raddatz, T.J., Roeckner, E., Schnur, R., Widmann, H., Claussen, M., Stevens, B. & Marotzke, J.* (2010): Climate and carbon-cycle variability over the last millennium.- Clim. Past 6: 723-737.

*Kageyama, M., Merkel, U., Otto-Bliesner, B., Prange, M., Abe-Ouchi, A., Lohmann, G., Roche, D.M., Singarayer, J., Swingedouw, D. & Zhang, X.* (2012): Climatic impacts of fresh water hosing under Last Glacial Maximum conditions: a multi-model study.- Clim. Past. 9: 935-953, SRef-*ID:1814-9332/cp/2013-9-935*.

*Kerr, R.A.* (2003): Who pushed whom out of the Last Ice Age?.- Science 299: 1645, doi: 10.1126/science.299.5613.1645.

*Kim, J.-H., Romero, OE., Lohmann, G., Donner, B., Laepple, T., Haam, E. & Damsté, J.S.S.* (2012): Pronounced subsurface cooling of North Atlantic waters off Northwest Africa during Dansgaard-Oeschger interstadials.- Earth Planet. Sci. Lett. 339–340: 95-102, doi: 10.1016/j.epsl.2012.05.018.

*Knorr, G.* (2003): Collapse and resumption of the thermohaline circulation during deglaciation: insights by models of different complexity.- PhD Thesis, University of Hamburg, Germany. 1-107.

*Knorr, G. & Lohmann, G.* (2003): Southern Ocean origin for resumption of Atlantic thermohaline circulation during deglaciation.- Nature 424: 532-536.

*Knorr, G. & Lohmann, G.* (2007): Transitions in the Atlantic thermohaline circulation by global deglacial warming and melt-water pulses.- Geochem. Geophys. Geosyst. 8, doi:10.1029/2007GC001604.

*Knorr, G. & Lohmann, G.* (2014): A warming climate during the Antarctic ice sheet growth at the Middle Miocene transition.- Nature Geosci. 7: 376-381, doi: 10.1038/NGEO2119

*Knorr, G., Butzin, M., Micheels, A. & Lohmann, G.* (2011): A warm Miocene climate at low atmospheric $CO_2$ levels.- Geophys. Res. Lett. 38: 1-5.

*Kwasniok, F. & Lohmann, G.* (2009): Deriving dynamical models from paleoclimatic records: application to glacial millennial-scale climate variability.- Phys. Rev. E 80: 066104, doi: 10.1103/PhysRevE.80.066104.

*Kwasniok, F. & Lohmann, G.* (2012): A stochastic nonlinear oscillator model for glacial millennial-scale climate transitions derived from ice-core data.- Nonlin. Processes Geophys. 19: 595-603, doi: 10.5194/npg-19-595-2012.

*Laepple, T., Werner, M. & Lohmann, G.* (2011): Synchronicity of Antarctic temperatures and local solar insolation on orbital time-scales. Nature 471: 91-94, doi: 10.1038/nature09825

*Langebroek, P., Werner, M. & Lohmann, G.* (2011): Climate information imprinted in oxygen-isotopic composition of precipitation in Europe.- Earth Planet. Sci. Lett. 311: 144-154, doi: 10.1016/j.epsl.2011.08.049.

*Liu, Z., Otto-Bliesner, B.L., He, F., Brady, E.C., Tomas, R., Clark, P.U., Carlson, A.E., Lynch-Stieglitz, J., Curry, W., Brook, E., Erickson, D., Jacob, R., Kutzbach, J. & Cheng, J.* (2009): Transient simulation of last deglaciation with a new mechanism for Bolling-Allerod warming.- Science 325: 310-314, doi: 10.1126/science.1171041.

*Liu, Z., Zhua, J., Rosenthal, Y., Zhang, X., Otto-Bliesner, B., Timmermann, A., Smith, R.S., Lohmann, G., Zheng, W. & Timm, O.E.* (2014): The Holocene temperature conundrum.- Proc. National Acad. Sci. USA 111: 3501-3505, doi: 10.1073/pnas.1407229111.

*Livina, V.N., Kwasniok, F., Lohmann, G., Kantelhardt, J.W. & Lenton, T.M.* (2011): Changing climate states and stability: from Pliocene to present.- Clim. Dyn. 37: 2437-2453, doi: 10.1007/s00382-010-0980-2.

*Lohmann, G.* (1998): The influence of a near-bottom transport parameterization on the sensitivity of the thermohaline circulation.- J. Phys. Oceanogr. 28: 2095-2103.

*Lohmann, G.* (2009): Abrupt climate change modeling.- In R.A. MEYERS (ed): Encyclopedia of Complexity and Systems Science 1: 1-21, Springer, New York, doi:10.1007/978-0-387-30440-3_1.

*Lohmann, G.* (2016): Atmospheric bridge on orbital time scales.- Theoretical and Applied Climatology, doi: 10.1007/s00704-015-1725-2.

*Lohmann, G. & Lorenz, S.* (2000): On the hydrological cycle under paleoclimatic conditions as derived from AGCM simulations.- J. Geophys. Res. Atmos. 105: 17417-17436.

*Lohmann, G. & Schulz, M.* (2000): Reconciling Bølling warmth with peak deglacial meltwater discharge.- Paleoceanography 15: 537-540.

*Lohmann, G. & Wiltshire, K.H.* (2012): Winter atmospheric circulation signature for the timing of the spring bloom of diatoms in the North Sea.- Marine Biology 159: 2573-2581. doi: 10.1007/s00227-012-1993-7

*Lohmann, G., Gerdes, R. & Chen, D.* (1996): Sensitivity of the thermohaline circulation in coupled oceanic GCM-atmospheric EBM experiments.- Climate Dynamics 12: 403-416.

*Lohmann, G., Butzin, M., Grosfeld, K., Knorr, G., Paul, A., Prange, M., Romanova, V. & Schubert, S.* (2003): The Bremen Earth System Model of Intermediate Comlexity (BREMIC) designed for long-term climate studies. Model description, climatology, and applications.- University Bremen, techn. Rep. <www.geo.uni-bremen.de/~gerrit/ BREMIC .html>

*Lohmann, G., Haak, H. & Jungclaus, J.H.* (2008): Estimating trends of Atlantic meridional overturning circulation from long-term hydrographic data and model simulations.- Ocean Dyn. 58: 127-138, doi: 10.1007/s10236-008-0136-7.

*Lohmann, G., Pfeiffer, M., Laepple, T., Leduc, G. & Kim, J.-H.* (2013): A model-data comparison of the Holocene global sea surface temperature evolution.- Clim. Past 9: 1807-1839, doi: 10.5194/cp-9-1807-2013.

*Lohmann, G., Butzin, M. & Bickert, T.* (2015): Effect of vegetation on the Late Miocene ocean circulation.- J. Mar. Sci. Eng. 3(4): 1311-1333, doi: 10.3390/jmse3041311.

*Lorenz, S. & Lohmann, G.* (2004): Acceleration technique for Milankovitch typeforcing in a coupled atmosphere-ocean circulation model: method and application for the Holocene.- Climate Dyn. 23: 727-743, doi: 10.1007/s00382-004-0469-y.

*Lunt, D.J., Williamson, M.S., Valdes, P.J., Lenton, T.M. & Marsh, R.* (2006): Comparing transient, accelerated, and equilibrium simulations of the last 30000 years with the GENIE-1 model.- Clim. Past 2: 221-235, doi: 10.5194/cp-2-221-2006.

*Lunt, D.J., Abe-Ouchi, A., Bakker, P., Berger, A., Braconnot, P., Charbit, S., Fischer, N., Herold, N., Jungclaus, J.H., Khon, V.C., Krebs-Kanzow, U., Lohmann, G., Otto-Bliesner, B., Park, W., Pfeiffer, M., Prange, M., Rachmayani, R., Renssen, H., Rosenbloom, N., Schneider, B., Stone, F. J., Takahashi, K., Wei, W. & Yin Q.* (2013): A multi-model assessment of last interglacial temperatures.- Clim. Past 9: 699-717, doi: 10.5194/cp-9-699-2013.

*Maier-Reimer, E., Mikolajewicz, U. & Hasselmann, K.* (1993): Mean circulation of the Hamburg LSG OGCM and its sensitivity to the thermohaline surface forcing.- J. Phys. Oceanogr. 23: 731-757.

*Marsland, S.J., Haak, H., Jungclaus, J.H., Latif, M. & Röske, F.* (2003): The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates.- Ocean Model. 5: 91-127.

*Martrat, B., Grimalt, J.O., Shackleton, N.J., de Abreu, L., Hutterli, M.A. & Stocker, T.F.* (2007): Four climate cycles of recurring deep and surface water destabilizations on the Iberian Margin.- Science 317: 502-507.

*Pfeiffer, M. & Lohmann, G.* (2016): Greenland Ice Sheet influence on Last Interglacial climate: global sensitivity studies performed with an atmosphere–ocean general circulation model.- Clim. Past 12: 1313-1338, doi:10.5194/cp-12-1313-2016.

*Prange, M., Romanova, V. & Lohmann, G.* (2002): The glacial thermohaline circulation: stable or unstable?.- Geophys. Res. Lett. 29: 2028, doi: 10.1029/2002GL015337.

*Prange, M., Lohmann, G. & Paul, A.* (2003): Influence of vertical mixing on the thermohaline hysteresis: Analyses of an OGCM.- J. Phys. Oceanogr. 33: 1707-1721.

*Rühlemann, C., Mulitza, S., Lohmann, G., Paul, A., Prange, M. & Wefer, G.* (2004): Intermediate depth warming in the tropical Atlantic related to weakened thermohaline circulation: Combining paleoclimate and modeling data for the last deglaciation.- Paleoceanography 19: PA1025, doi: 10.1029/2003PA000948.

*Roche, D.M., Wiersma, A.P. & Renssen, H.* (2010): A systematic study of the impact of freshwater pulses with respect to different geographical locations.- Clim. Dyn. 34: 997-1013, doi: 10.1007/s00382-009-0578-8.

*Rodgers, K., Lohmann, G., Lorenz, S., Schneider, R. & Henderson, G.* (2003): A tropical mechanism for Northern Hemisphere deglaciation.- Geochem. Geophys. Geosyst. 4: 1046, doi: 10.1029/2003GC0000508.

*Roeckner, E., Arpe, K., Bengtsson, L., Brinkop, S., Dümenil, L., Esch, M., Kirk, E., Lunkeit, F., Ponater, M., Rockel, B., Sausen, R., Schleese, U., Schubert, S. & Windelband, M.* (1992): Simulation of the present-day climate with the ECHAM model: Impact of model physics and resolution.- Max-Planck Institut für Meteorologie, Hamburg, 1-171.

*Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U. & Tompkins, A.* (2003): The Atmospheric General Circulation Model ECHAM5. Part 1: Model Description.- Max-Planck-Institut für Meteorologie, Report 349: 1-140.

*Romanova, V., Prange, M. & Lohmann, G.* (2004): Stability of the glacial thermohaline circulation and its dependence on the background hydrological cycle.- Clim. Dyn. 22: 527-538.

*Salzmann, U., Dolan, A.M., Haywood, A.M., Chan, W.-L., Hill, D.J., Abe-Ouchi, A., Otto-Bliesner, B., Bragg, F., Chandler, M.A., Contoux, C., Jost, A., Kamae, Y., Lohmann, G., Lunt, D.J., Pickering, S.J., Pound, M.J., Ramstein, G., Rosenbloom, N.A., Sohl, L., Stepanek, C., Ueda, H. & Zhang, Z.* (2013): Challenges in quantifying Pliocene terrestrial warming revealed by data-model discord.- Nature Clim. Change 3: 969-974, doi: 10.1038/nclimate2008.

*Schäfer-Neth, C. & Paul, A.* (2001): Circulation of the glacial Atlantic: a synthesis of global and regional modeling.- In: P. Schäfer, W. Ritzrau, M. Schlüter & J. Thiede (eds): The northern North Atlantic: A changing environment, Springer-Verlag, Berlin, Heidelberg, 446-462.

*Schulz, M., Berger, W.H., Sarnthein, M. & Grootes, P.M.* (1999): Amplitude variations of 1470-year climate oscillations during the last 100,000 years linked to fluctuations of continental ice mass.- Geophys. Res. Lett. 26: 3385-3388.

*Stärz, M., Lohmann, G. & Knorr, G.* (2016): The effect of a dynamic soil scheme on the climate of the mid-Holocene and the Last Glacial Maximum.- Clim. Past 12: 151-170. doi :10.5194/cp-12-151-2016.

*Stepanek, C. & Lohmann, G.* (2012): Modelling mid-Pliocene climate with COSMOS.- Geosci. Model Dev. 5: 1221-1243, doi: 10.5194/gmd-5-1221-2012.

*Stepanek, C. & Lohmann, G.* (2016): Towards a more exible representation of hydrological discharge transport in (paleo-)climate modelling.- Polarforschung, 85: 171–177.

*Stocker, T.F.* (2003): Global change: South dials north.- Nature 424: 496-499, doi: 10.1038/424496a.

*Sutter, J., Thoma, M. & Lohmann, G.* (2015): Integration of passive tracers in a three-dimensional ice sheet model.- In: G. LOHMANN, H. MEGGERS, V. UNNITHAN, D. WOLF-GLADROW, J. NOTHOLT, A. BRACHER (eds), Towards an Interdisciplinary Approach in Earth System Science, Springer Earth System Sciences, Heidelberg, 161-170, doi: 10.1007/978-3-319-13865-7_18.

*Sutter, J., Gierz, P., Grosfeld, K., Thoma, M. & Lohmann, G.* (2016): Ocean temperature thresholds for Last Interglacial West Antarctic Ice Sheet collapse.- Geophys. Res. Lett. doi: 10.1002/2016GL067818.

*Swingedouw, D., Fichefet, T., Goosse, H. & Loutre, M.F.* (2009): Impact of transient freshwater releases in the Southern Ocean on the AMOC and climate.- Clim. Dyn. 33: 365-381, doi: 10.1007/s00382-008-0496-1.

*Timmermann, A. & Lohmann, G.* (2000): Noise-induced transitions in a simplified model of the thermohaline circulation.- J. Phys. Oceanogr. 30: 1891-1900.

*Timm, O. & Timmermann, A.* (2007): Simulation of the last 21 000 years using accelerated transient boundary conditions.- J. Clim. 20: 4377-4401, doi: org/10.1175/JCLI4237.1.

*Varma, V., Prange, M., Merkel, U., Kleinen, T., Lohmann, G., Pfeiffer, M., Renssen, H., Wagner, A., Wagner, S, & Schulz, M.* (2012): Holocene evolution of the Southern Hemisphere westerly winds in transient simulations with global climate models.- Clim. Past. 8: 391-402. doi: 10.5194/cp-8-391-2012.

*Wang, Z. & Mysak, L.A.* (2006): Glacial abrupt climate changes and Dansgaard-Oeschger oscillations in a coupled climate model.- Paleoceanography 21: PA2001, doi:10.1029/2005PA001238.

*Weaver, A.J., Saenko, O.A., Clark, P.U. & Mitrovica, J.X.* (2003): Meltwater pulse 1A from Antarctica as a trigger of the Bolling-Allerod warm interval.- Science 299: 1709-1713, doi: 10.1126/science.1081002.

*Weber, M.E., Clark, P.U., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M.O., Friedrich, T. & Ohlwein, C.* (2014): Millennial-scale variability in Antarctic ice-sheet

discharge during the last deglaciation.- Nature 510: 134-138, doi: 10.1038/nature13397.
*Wei, W. & Lohmann, G.* (2012): Simulated Atlantic multidecadal oscillation during the Holocene.- J. Clim. 25: 6989-7002, doi: 10.1175/JCLI-D-11-00667.1.
*Wei, W., Lohmann, G. & Dima, M.* (2012): Distinct modes of internal variability in the global meridional overturning circulation associated to the Southern Hemisphere westerly winds.- J. Phys. Oceanogr. 42: 785-801, doi: 10.1175/JPO-D-11-038.1.
*Werner, M., Langebroek, P.M., Carlsen, T, Herold, M. & Lohmann, G.* (2011): Stable water isotopes in the ECHAM5 general circulation model: Towards high-resolution isotope modeling on a global scale.- J. Geophys. *Res. - Atmos. 116: D15109, doi: 10.1029/2011JD015681.*
*Werner, M., Haese, B., Xu, X., Zhang, X., Butzin, M. & Lohmann, G.* (2016): Glacial-interglacial changes of $H_2{}^{18}O$, HDO and deuterium excess – results from the fully coupled ECHAM5/MPI-OM Earth System Model.- Geosci. Model Dev. 9: 647-670, doi: 10.5194/gmd-9-647-2016.
*Winton, M.* (1993): Deep decoupling oscillations of the ocean thermohaline circulation.- In: W. PELTIER (ed): Ice in the Climate System, Springer, New York, 417-432.
*Xu, X., Werner, M., Butzin, M. & Lohmann, G.* (2012): Water isotope variations in the global ocean model MPI-OM.- Geosci. Model Dev. 5: 809-818.
*Zhang, X., Lohmann, G., Knorr, G. & Purcell, C.* (2014): Control of rapid glacial climate shifts by variations in intermediate ice-sheet volume.- Nature 512: 290-294, doi: 10.1038/nature13592.
*Zhang, X., Lohmann, G., Knorr, G. & Xu, X.* (2013): Different ocean states and transient characteristics in Last Glacial Maximum simulations and implications for deglaciation.- Clim. Past 9: 2319-2333, doi: 10.5194/cp-9-2319-2013.
*Zhu, J., Liu, Z., Zhang, X., Eisenman, I. & Liu W.* (2014): Linear weakening of the AMOC in response to receding glacial ice sheets in CCSM3.- Geophys. Res. Lett. 41: 6252-6258.
*Zhu, J., Liu, Z., Zhang, J. & Liu, W.* (2015): AMOC response to global warming: dependence on the background climate and response time scale.- Clim. Dyn. 44 (11): 3449-3468.